

Final Report

Remote Sensing and Modeling of Coherent Structures in River and Estuarine Flows

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Award Number: N00014-05-1-0485

LONG-TERM GOALS

The long-term goals of this research were to combine state-of-the-art remote sensing and *in situ* measurements with advanced numerical modeling (a) to characterize coherent structures in river and estuarine flows and (b) to determine the extent to which their remotely sensed signatures can be used to initialize and guide predictive models.

OBJECTIVES

Coherent structures are generated by the interaction of the flow with bathymetric and coastline features. These coherent structures produce surface signatures that can be detected and quantified using remote sensing techniques. Furthermore, a number of relationships between coherent structures and flow characteristics have been suggested that have the potential to allow flow parameters (e.g. mean velocity, bottom roughness, shear, and turbidity) to be inferred from remote measurements. The objectives were to test the following four hypotheses:

1. Flow parameters can be inferred from remotely sensed signatures of coherent structures.
2. Numerical models can be constrained with these inferred parameters.
3. The effect of stratification on the strength of coherent structures can be used to detect the presence or absence of stratification and the location of the fresh/salt water interface.
4. Numerical and field experiments can be used together to predict, interpret, characterize, and understand coherent structures.

APPROACH

The key to this project was an interactive process that blended sophisticated remote sensing, *in situ* measurements, and numerical simulation. Our approach was to conduct closely coupled field and numerical model experiments to test the hypotheses listed above. We conducted two major field experiments with both *in situ* and remote sensing measurements – the first was in Year 2 and the second in Year 4. Preliminary experiments were conducted in Years 1 and 3 to aid in the

design of the major field efforts. The research involved four main areas - (1) *in situ* measurements, (2) remote sensing, (3) modeling, and (4) physics and classification of coherent structures. The *in situ* field measurements were used to characterize the overall flow field to investigate the generation of coherent structures at specific sites, and initially, to provide boundary inputs for the numerical models. The surface signatures of coherent structures in the same region were detected using remote sensing techniques and compared with the *in situ* and model results. The numerical models served three roles, viz., (1) precursor simulations in which existing bathymetry and assumed regional forcing will allow us to guide the measurement plans, (2) detailed simulations of both the region and specific local areas for comparison to field-determined coherent structures, and (3) simulations to aid in characterizing the mechanisms by which observed coherent structures are formed, to evaluate the sensitivity of these generation mechanisms to variations in forcing, and to predict the surface signature that such structures generate. Results from the *in situ* field observations, remote sensing, and numerical model runs were synthesized into a classification scheme that included all observed coherent structures. Predictive scaling relationships were developed in order to generalize the results from this study to other systems. The result of this integrated approach were a thorough investigation of the mechanisms and evolution of coherent structures in rivers and estuaries in order to link their surface expressions to subsurface flow features.

The project participants were organized into teams identified by the main areas of interest listed above: Remote Sensing: A. Jessup, W. Plant (APL-UW); Modeling: R. Street and O. Fringer (Stanford); In situ Measurements: S. Monismith and D. Fong (Stanford); Physics and Classification: A. Horner-Devine.

The project supported one MS student (Brownyn Hayward, UW-CEE), two PhD students (Sarah Giddings and Bing Wang, Stanford-CEE), and two postdoctoral fellows (Chris Chickadel, APL-UW, and Mike Barad, Stanford-CEE).

To date, the project has produced 7 published and 2 submitted peer-reviewed journal articles, 1 MS thesis, and 2 PhD theses. We anticipate that at least 3 additional manuscripts will be submitted to peer-reviewed publications within the next year.

The results of the project to date are summarized in the following publications:

Articles in Peer-Reviewed Journals: Published

1. Chickadel, C., S. Talke, A. Horner-Devine, and A. Jessup (2011), Infrared based measurements of velocity, turbulent kinetic energy, and dissipation at the water surface in a tidal river, *Geosci. Rem. Sen. Let.*, *in press*.

Abstract

Thermal infrared (IR) imaging is used to measure the evolution of velocity, turbulent kinetic energy (TKE), and the TKE dissipation rate at the water surface in the tidally influenced Snohomish River. Patterns of temperature variability in the IR imagery arise from disruption of the cool skin layer and are used to extract the 2D velocity field through phase-correlation particle image velocimetry (PIV). Comparisons of IR based PIV mean velocity made against a collocated acoustic velocimeter demonstrate high correlation ($r^2 > 0.9$). Over a tidal period, surface TKE computed from the IR velocity varies from 10^{-4} J kg⁻¹ to 3×10^{-3} J kg⁻¹, with an average difference from the *in situ* measurements of 8%. IR-derived TKE dissipation rates vary from approximately 3×10^{-6} W kg⁻¹ to 2×10^{-4} W kg⁻¹ at peak ebb, agreeing on average to within 7% of the *in situ*

velocimeter results. Infrared-based PIV provides quantitative and detailed measurements of previously inaccessible surface flow and turbulence statistics.

2. Chickadel, C. C., A. R. Horner-Devine, S. A. Talke, and A. T. Jessup (2009), Vertical boil propagation from a submerged estuarine sill, *Geophysical Research Letters*, 36.

Abstract

Surface disruptions by boils during strong tidal flows over a rocky sill were observed in thermal infrared imagery collected at the Snohomish River estuary in Washington State. Locations of boil disruptions and boil diameters at the surface were quantified and are used to test an idealized model of vertical boil propagation. The model is developed as a two-dimensional approximation of a three-dimensional vortex loop, and boil vorticity is derived from the flow shear over the sill. Predictions of boil disruption locations were determined from the modeled vertical velocity, the sill depth, and the over-sill velocity. Predictions by the vertical velocity model agree well with measured locations (rms difference 3.0 m) and improve by using measured velocity and shear (rms difference 1.8 m). In comparison, a boil-surfacing model derived from laboratory turbulent mixed-layer wakes agrees with the measurements only when stratification is insignificant.

3. Giddings, S. N., D. A. Fong, and S. G. Monismith (2011b), Role of straining and advection in the intratidal evolution of stratification, vertical mixing, and longitudinal dispersion of a shallow, macrotidal, salt wedge estuary, *J. Geophys. Res.-Oceans*, 116.

Abstract

A month of flow observations in the Snohomish River Estuary reveals the complex intratidal and fortnightly stratification, mixing, and dispersion dynamics in this macrotidal, shallow, salt wedge estuary system. Both salt wedge propagation and concomitant straining of the density field dominate temporal and spatial variations in stratification leading to intratidal variability of shear and mixing that differs in important ways from observations in partially mixed estuaries. Bottom-generated turbulent kinetic energy production is enhanced during spring tides and acts in concert with straining to counteract advection and minimize vertical stratification during the spring flood tides. This bottom-generated mixing contributes to a buoyancy flux near the top of a well-mixed layer during strong flood tides. During strong ebb tides, interfacial shear production and buoyancy flux occur along the sharp straining-enhanced interface just before the system becomes well mixed. Longitudinal dispersion is less sensitive to the spring/neap cycle yet exhibits strong intratidal variability. Reduced longitudinal dispersion is observed during the large floods relative to the rest of the tidal cycle, behavior we attribute to a lack of vertical shear. Overall, ebb tide advection and straining enhance stratification and longitudinal dispersion and allow for interfacial mixing. Intratidal variability, which varies on the spring/neap scale, is a dominant feature of this estuary, suggesting the importance of intratidal processes and tidally varying mixing coefficients in similar strongly stratified, strongly forced estuaries.

4. Plant, W. J., et al. (2009), Remotely sensed river surface features compared with modeling and in situ measurements, *J. Geophys. Res.-Oceans*, 114.

Abstract

Images of river surface features that reflect the bathymetry and flow in the river have been obtained using remote sensing at microwave, visible, and infrared frequencies. The experiments were conducted at Jetty Island near the mouth of the Snohomish River at Everett, Washington, where complex tidal flow occurs over a varied bathymetry, which was measured as part of these experiments. An X band (9.36 GHz) Doppler radar was operated from the river bank and produced images of normalized radar cross sections and radial surface velocities every 20 min over many tidal cycles. The visible and infrared instruments were flown in an airplane. All of these techniques showed surface evidence of frontal features, flow over a sill, and flow conditioned by a deep hole. These features were modeled numerically, and the model results correspond well to the remote observations. In situ measurements made near the hole showed that changes in measured velocities correlate well with the occurrence of the features in the images. In addition to tidal phase, the occurrence of these features in the imagery depends on tidal range. The surface roughness observed in the imagery appears to be generated by the bathymetry and flow themselves rather than by the modulation of wind waves.

5. Talke, S. A., A. R. Horner-Devine, and C. C. Chickadel (2010), Mixing layer dynamics in separated flow over an estuarine sill with variable stratification, *J. Geophys. Res.-Oceans*, 115.

Abstract

The parallel, finite-volume, unstructured-grid SUNTANS model We investigate the generation of a mixing layer in the separated flow behind an estuarine sill (height $H \sim 4$ m) in the Snohomish River, Washington as part of a larger investigation of coherent structures using remote and in situ sensing. During increasing ebb flows the depth d and stratification decrease and a region of sheared flow characterized by elevated production of turbulent kinetic energy develops. Profiles of velocity and acoustic backscatter exhibit coherent fluctuations of order 0.1 Hz and are used to define the boundaries of the mixing layer. Variations in the mixing layer width and its embedded coherent structures are caused by changes to both the normalized sill height H/d and to a bulk Richardson number Ri_h defined using the depth of flow over the sill. Entrainment E_T and the mixing layer expansion angle increase as stratification and the bulk Richardson number decrease; this relationship is parameterized as $E_T = 0.07 Ri_h^{-0.5}$ and is valid for approximately $0.1 < Ri_h < 2.8$. Available comparisons with literature for inertially dominated conditions ($Ri_h < 0.1$) are consistent with our data and validate our approach, though lateral gradients may introduce an upwards bias of approximately 20%. As the ratio H/d increases over the ebb, the free surface boundary pushes the mixing layer trajectory downward, reduces its expansion angle, and produces asymmetry in the acoustic backscatter (coherent structures). Three-dimensional divergence, as imaged by infrared video and transecting data, becomes more prominent for $H/d > 0.8$ due to blocking of flow by the sill.

6. Wang, B., O. B. Fringer, S. N. Giddings, and D. A. Fong (2009), High-resolution simulations of a macrotidal estuary using SUNTANS, *Ocean Modelling*, 28(1-3), 167-192.

Abstract

The parallel, finite-volume, unstructured-grid SUNTANS model has been employed to study the interaction of the tides with complex bathymetry in the macrotidal Snohomish River estuary. The unstructured grid resolves the large-scale, $O(10$ km) tidal dynamics of the estuary while employing 8 m grid-resolution at a specific region of interest in the vicinity of a confluence of two channels and extensive intertidal mudflats to understand detailed local intratidal flow processes. After calibrating tidal forcing parameters to enforce a match between free surface and depth-averaged velocities at several locations throughout the domain, we analyze the complex dynamics of the confluence and show that the exposure of the intertidal mudflats during low tide induces a complex flow reversal. When coupled with the longitudinal salinity gradient, this flow reversal results in a highly variable salinity field, which has profound implications for local mixing, stratification and the occurrence of fine-scale flow structures. This complex flow is then used as a testbed from which to describe several challenges associated with high resolution modeling of macrotidal estuaries, including specification of high resolution bathymetry, specification of the bottom stress, computation of the nonhydrostatic pressure, accurate advection of momentum, and the influence of the freshwater inflow. The results indicate that with high resolution comes the added difficulty of requiring more accurate specification of boundary conditions. In particular, the bottom bathymetry plays the most important role in achieving accurate predictions when high resolution is employed

7. Wang, B., et al. (2010), Modeling and understanding turbulent mixing in a macrotidal salt wedge estuary, *J. Geophys. Res.-Oceans*, 116.

Abstract

A high-resolution three-dimensional numerical simulation is performed with the parallel, unstructured grid SUNTANS model to study the spatiotemporal dynamics of turbulent mixing in a shallow, macrotidal salt wedge estuary that experiences periodic mixing and strong stratification. Unresolved vertical mixing is parameterized with the $k - \kappa_l$ closure scheme with the Canuto-A stability functions based on a careful comparison of multiple two-equation closure schemes and stability functions via the generic length scale approach. The predictions of velocity, salinity, Richardson number, and Reynolds stress are in good agreement with field observations, and the top and bottom salinity predictions achieve skill scores of 0.86 and 0.91, respectively. The model shows that the salt wedge starts to strengthen upstream at the beginning of weak ebb and gradually expands downstream during the weak tide. Mixing is most active along a density interface during the weak ebb, while it is most active in a bottom mixed layer during weak flood, consistent with the findings inferred from the observations. Stratification decays during the strong ebb in a mixing event along the horizontal extent of the salt wedge while it is also being advected offshore. Local mixing is shown to account for roughly half of the decay rate of the stratification in this process. Numerical

experiments are performed to investigate the response of stratification and mixing to changes in the magnitude of the buoyancy. High sensitivity is shown under intermediate levels of stratification that occur in the real system, which becomes considerably weaker under more extreme conditions.

Articles in Peer-Reviewed Journals: In Review

1. Giddings, S. N., et al. (2011a), Frontogenesis and frontal progression of a trapping-generated estuarine convergence front and its influence on mixing and stratification, *Estuaries and Coast*, in review.

Abstract

Complex bathymetry and a large tidal range in the Snohomish River Estuary lead to trapping of mid-density water over intertidal mudflats. The convergence of this water mass with dense water in the main channel forms a sharp front. The frontal density interface is maintained via convergent transverse circulations driven by the competition of lateral baroclinic and centrifugal forcing. Spatial and temporal variations in stratification and vertical mixing result from the frontal presence and propagation. Importantly, this front leads to enhanced stratification and suppressed vertical mixing at the end of the large flood tide, in contrast to what is found in many estuarine systems. This front does not significantly alter longitudinal dispersion; however, this type of trapping-driven front may contribute to longitudinal dispersion in estuaries with larger trapping regions. This mechanism fits within the broader context of bathymetrically driven frontogenesis mechanisms in which varying bathymetry drives lateral convergence and baroclinic forcing.

2. Wang, B., G. Zhao, and O. Fringer (2011), Reconstruction of vector fields for semi-Lagrangian advection on unstructured, staggered grids, *Ocean Modelling*, in review.

Abstract

Applying the semi-Lagrangian method to discretize the advection of momentum eliminates the Courant number constraint associated with momentum advection in coastal ocean models. Key steps of the semi-Lagrangian method include calculating trajectories and interpolating the velocity vectors at the end of trajectories. In this work, we follow the linear and quadratic interpolation methods proposed by Walters et al. (2007) for τ -eld-scale simulations on unstructured, staggered grids and compare their performance using a backward-facing step test case and τ -eld-scale estuarine simulations. A series of common methods to approximate the nodal and tangential velocities needed for the interpolation are evaluated and it is found that the methods based on RT0 basis functions are more robust with respect to grid quality than the methods from Perot (2000) while overall they obtain similar accuracy. Over the range of different nodal and tangential velocities, the quadratic interpolation methods consistently exhibit higher accuracy than the linear interpolation methods. For the quadratic interpolation, the overall accuracy depends on the approximation of the tangential velocity and the backward-facing step test case indicates that the quadratic interpolation behaves like Eulerian central differencing or τ -st-order upwinding, depending on the tangential approximations. The τ -eld-scale estuarine flow test case also shows general improvement on the velocity predictions and sharper gradients in the velocity τ -eld with the quadratic interpolation. The quadratic interpolations add less than 15% to the total computation time, and parallel implementation is relatively straightforward in complex geometries.

Dissertations

1. Giddings, S. (2010), Dynamics of a shallow, macrotidal, strongly stratified estuary, PhD Dissertation, Stanford University.
2. Hayworth, B. (2007), Observations of Tidally Generated Coherent Structures in the Snohomish River Estuary, MS Dissertation, University of Washington.
3. Wang, B. (2011), Multiscale numerical simulation of a complex macrotidal tidal-river estuary, PhD Dissertation, Stanford University.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 31 March 2011		2. REPORT TYPE Final Report			3. DATES COVERED (From - To) 1 July 2006 - 31 December 2010	
4. TITLE AND SUBTITLE Final Report Remote Sensing and Modeling of Coherent Structures in River and Estuarine Flows				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER N00014-05-1-0485		
				5c. PROGRAM ELEMENT NUMBER		
				5d. PROJECT NUMBER		
6. AUTHOR(S) Andrew T. Jessup Robert L. Street Stephen G. Monismith Alexander R. Horner-Devine				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory - University of Washington 1013 NE 40th Street Seattle, WA 98105-6698				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research (ONR 322) 875 North Randolph Street Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Statement A. Approved for public release; distribution is unlimited						
13. SUPPLEMENTARY NOTES None						
14. ABSTRACT The COHSTREX (Coherent Structures in Rivers and Estuaries Experiment) project was implemented to determine the extent to which the remotely-sensed signatures of coherent structures can be used to initialize and constrain predictive models for river and estuarine flows. Infrared and microwave techniques that are mature and proven were used to detect and quantify coherent structures. An existing set of sophisticated codes for accurate simulation of three-dimensional unsteady fluid motions and scalar transports was used as the basis of the modeling effort. Our results demonstrated how currently available prediction schemes and observing systems (remote sensing and AUVs) can be combined for maximum operational impact.						
15. SUBJECT TERMS Coherent Structures, Infrared, River, Estuary						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Andrew T. Jessup	
U	U	U	UU		19b. TELEPHONE NUMBER (Include area code) 206-685-2609	

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